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(t,He^4) Reaction on the Even Ni Isotopes

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A beam of 15-MeV tritons was used to bombard thin targets of Ni^{58}, Ni^{60}, Ni^{62}, and Ni^{64}. States up to several MeV of excitation in Co^{57}, Co^{59}, Co^{61}, and Co^{63} were observed by means of the (t,He^4) reaction. Spin and parity assignments were made by comparing the experimental angular distributions with distributions from states whose assignments are known, by comparing them with the predictions of a distorted-wave calculation, and from shell-model considerations. In the reaction to each of the four Co nuclides, we observed several $f_{7/2}$ transitions in addition to the strong $f_{7/2}$ ground-state transition, one to three relatively weak $p_{3/2}$ transitions, and two strong transitions representing the major fragments of the $(2s_{1/2})^{-1}$ and $(1d_{3/2})^{-1}$ shell-model states. The $s_{1/2}$ transition occurs at a lower excitation energy than the $d_{3/2}$ transition, an ordering which is the inverse of that previously observed in the (d,He^3) reaction on Ti nuclides. There is no evidence that the strong Q dependence of angular distributions previously observed in the (He^4,t) reaction occurs in the (t,He^4) reaction. The distorted-wave calculation comparison suggests that refinements in the calculation are needed.

I. INTRODUCTION

Although there have been numerous studies of neutron particle and hole states by means of neutron stripping and pickup reactions, similar studies of proton states are far less abundant and have usually been restricted to the light-mass region. Recently, however, several studies of the (He^3,d) reaction on medium-mass nuclei have been reported and there is continuing interest in the investigation of proton-particle states by means of this reaction. There have also been reports of investigations of proton-hole states, but the number of such investigations is limited by experimental considerations. Possible reactions for such studies include the (n,d), (d,He^3), and (t,He^4) reactions. Of these, the (n,d) reaction suffers from low beam intensities and relatively poor resolution; the (d,He^3) reaction, if beam energies are below approximately 20 MeV, is often sensitive to the Coulomb barrier in the outgoing channel; the (t,He^4) reaction, while possessing a large reaction Q, requires a primary beam of particles which is not commonly available.

The reaction mechanism of the (t,He^4) reaction is more poorly understood than is that of the (d,He^3) or the (n,d) reaction. The usual interpretation of experimental results from the (t,He^4) reaction [and the similar (He^3,He^4) reaction], at incident energies above 8 or 10 MeV, is in terms of the simple pickup reaction, for which an analysis by means of the distorted-wave (DW) approximation is applicable. A recent study[1] of the inverse (He^4,t) reaction has yielded results, however, that are in poor agreement with some of the predictions of a DW calculation.

We have begun our studies of the (t,He^4) reaction in the medium-mass region, and present in this paper the results for targets of the even-even Ni isotopes leading to states in $Co^{57,59,61,63}$. Some previous spectroscopic information exists for the Co^{57} and Co^{59} nuclides, but there is relatively little information about the states of Co^{61} and Co^{63}. To our knowledge, there have been no previous studies of the (t,He^4) reaction in the medium-mass region, although there have been some recent investigations in the Pb region.[2] Of the four nuclides included in the present report, Co^{57} has been studied by means of the Ni^{58}(n,d) reaction.[3] In addition, a brief account of the (d,He^3) reaction on Ni^{58} and Ni^{60} has been given by Yntema *et al.*,[4] and the Ni^{58}(d,He^3) reaction to the ground state of Co^{57} has been investigated by Čujec.[5]

II. EXPERIMENTAL PROCEDURE

A 15.0-MeV triton beam, obtained from the Los Alamos three-state Van de Graaff accelerator, was focused as a $\frac{1}{16}\times\frac{5}{32}$-in. vertical spot on a target at the center of a 20-in.-diam scattering chamber. The reaction He^4 ions were detected in a commercially obtained 500-μ gold surface-barrier detector mounted on an internal arm whose azimuthal angular position could be set and read remotely. The amplified detector pulses were fed into a 400-channel pulse-height analyzer, and the resulting spectra were read out as information on punched paper tape. After conversion into information on IBM cards or magnetic tape, the data were analyzed with the aid of a least-squares computer program[6] which fits a skewed Gaussian distribution plus an exponential tail to each peak in a pulse-height spectrum and computes the area of each peak.

The self-supporting targets were produced by vacuum evaporation,[7] and had areal densities, determined to an

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[6] P. T. McWilliams, W. S. Hall, and H. E. Wegner, Rev. Sci. Instr. **33**, 70 (1962); W. S. Hall (private communication).

[7] We are indebted to L. Allen of this laboratory for the preparation of these targets.

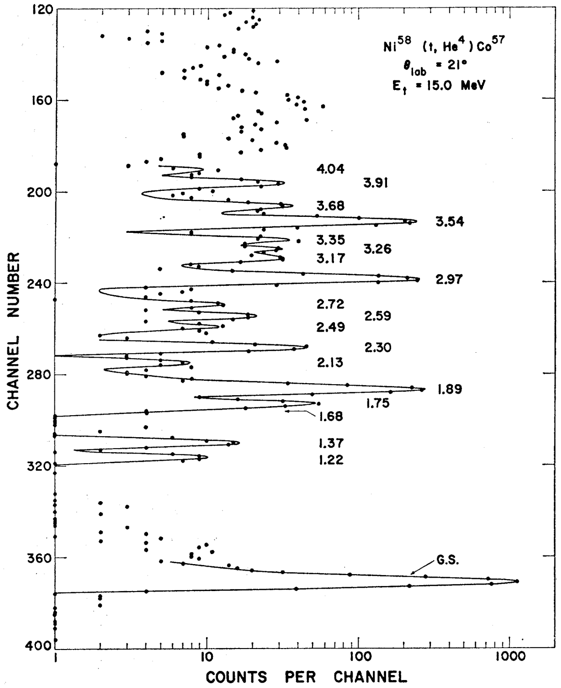

FIG. 1. Pulse-height spectrum of He^4 ions from the Ni^{58}(t,He^4) Co^{57} reaction. The curves through the datum points represent the results of a least-squares computer program which fits each peak with a skewed Gaussian distribution plus an exponential tail. States are labeled with their excitation energies in MeV.

accuracy of ±10% in earlier experiments,[8,9] ranging between 150 and 600 μg/cm^2. The isotopic purity of the target material[10] was 99.9%, 99.8%, 98.7%, and 98.6% for the Ni^{58}, Ni^{60}, Ni^{62}, and Ni^{64} targets, respectively.

Depending on the target thickness, the over-all energy resolution of the He^4-ion spectra varied between 40 and 55 keV. The detector geometry was set up to yield an angular resolution of approximately 0.5°. Zero scattering angle was determined to ±0.2°, while relative scattering angles were set to an accuracy of ±0.1°.

After passing through the target, the triton beam was collected in a Faraday cup, and the total charge for each experimental run was measured by a current-to-frequency integrator.[11]

The energy scale of the He^4-ion spectra was obtained by reference to the positions of the lower states of Mg^{26},[12] excited by means of the Al^{27}(t,He^4) reaction, and by the positions of the ground states[13] of N^{15} and B^{11} excited by means of the (t,He^4) reactions on the O^{16} and C^{12} contaminants in the targets.

The error bars shown in the angular distributions represent standard deviations plus, in the case of higher excited states, an estimate of the uncertainty in the background subtraction.

III. RESULTS

A. Ni^{58}(t,He^4)Co^{57} Reaction

The ground-state Q for the Ni^{58}(t,He^4)Co^{57} reaction is 11.636 MeV.[13] A typical energy spectrum for this reaction is shown in Fig. 1. The spectrum is dominated by peaks corresponding to Co^{57} states at 0, 1.89, 2.97, and 3.54 MeV. Figure 2 shows angular distributions of He^4 ions from these and some of the other Co^{57} states.

Although the Ni nuclei contain 28 protons, which normally are considered to fill the $1f_{7/2}$ proton shell, there is previous evidence[8] that the shell closure is not complete and that, in the ground-state wave functions, there must be configurations of protons occupying one or more of the higher orbitals. Because the $2p_{3/2}$ orbital is the first orbital encountered above the $1f_{7/2}$ shell, and the next orbitals ($1f_{5/2}$ and $2p_{1/2}$) are higher by an additional 2 MeV or so,[8,9] a reasonable assumption is that in the ground-state wave functions of the Ni nuclei no configurations or proton orbitals higher than $2p_{3/2}$ contribute importantly. This assumption forms one basis for spin assignments made in the present paper, but its reliability is examined frequently.

The spin and parity of the ground state and the 1.37-MeV state of Co^{57} are known to be $J^\pi=\frac{7}{2}^-$ and $J^\pi=\frac{3}{2}^-$,

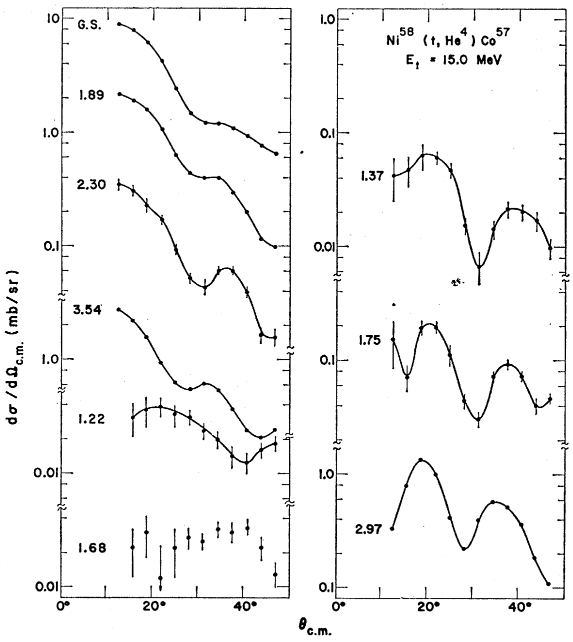

FIG. 2. Angular distributions of some of the He^4-ion groups from the Ni^{58}(t,He^4) Co^{57} reaction. The curves drawn through the experimental points are intended only as visual guides.

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[8] A. G. Blair, Phys. Rev. **140**, B648 (1965).

[9] A. G. Blair, *Comptes Rendus du Congrès International de Physique Nucléaire* (Éditions du Centre National de la Recherche Scientific, Paris, 1964), Vol. II, p. 471.

[10] Oak Ridge National Laboratory, Isotopes Division, Oak Ridge, Tennessee.

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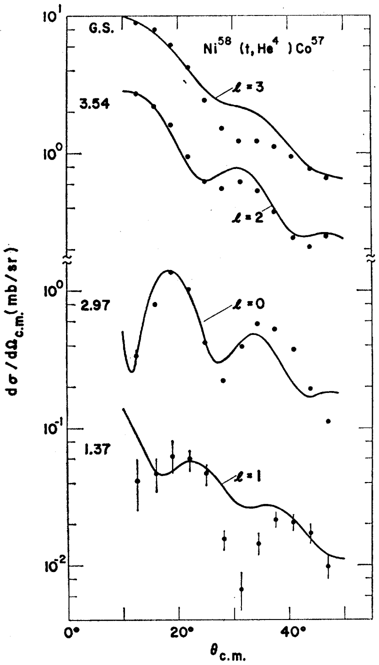

FIG. 3. Comparison of the predictions of the DW calculation to the ground-state, 1.37-, 2.97-, and 3.54-MeV distributions from the $Ni^{58}(t,He^4)Co^{57}$ reaction.

respectively.[14–16] Thus these transitions represent $f_{7/2}$ and $p_{3/2}$ proton pickups. Of the three remaining strong transitions shown in Figs. 1 and 2, the one at 1.89 MeV is also identified as an $f_{7/2}$ pickup from the similarity of its distribution to that of the ground state. The strongly excited states at 2.97 MeV and 3.54 MeV have distributions which are different from each other and from the ground-state and the 1.37-MeV-state distributions. In each of the Co nuclei two strong transitions whose distributions closely resemble the Co^{57} 2.97-MeV and 3.54-MeV distributions are observed in this region of excitation energy. One would expect to pick up $1d_{3/2}$ and $2s_{1/2}$ protons at approximately this energy[17,18] and it is reasonable to consider that these two distributions represent such transitions.

TABLE I. Values of optical-model parameters used in present DW calculation.

	V (MeV)	r_0 (F)	a (F)	W (MeV)	r_0' (F)	a' (F)	r_{0c} (F)
Tritons (15 MeV)[a]	151.0	1.24	0.692	29.0	1.36	0.890	1.25
He^4 ion (24.7 MeV)[b]	206.8	1.41	0.519	25.8	1.41	0.519	1.30

[a] Values from Ref. 21. [b] Values from Ref. 20.

In Fig. 3, four of the distributions are reproduced and are compared to results from a distorted-wave (DW) calculation.[19] This calculation employs the zero-range approximation and treats all particles as though they were spinless. The optical-model parameters for the He^4 ions are for scattering from natural Ni, and are taken from the recent analysis of McFadden and Satchler.[20] The triton optical-model parameters were obtained from fits to angular distributions of tritons elastically scattered from Ni^{62}.[21] One would prefer to use parameters appropriate to the specific nuclide involved in the reaction, but these are not available. Table I lists the paremeters used; the form of the potential is given by

$$U(r) = -V(e^x+1)^{-1} - iW(e^{x'}+1)^{-1} + U_c(r).$$

Here,

$$x = (r - r_0A^{1/3})/a, \quad x' = (r - r_0'A^{1/3})/a',$$

and U_c is the Coulomb potential from a uniformly charged sphere of radius $r_{0c}A^{1/3}$. Although an energy dependence in the He^4-ion channel of $\Delta V/\Delta E = -0.4$ MeV/MeV and $\Delta W/\Delta E = +0.1$ MeV/MeV was used, the DW calculation was insensitive to this variation. Several other sets[20,21] of optical-model parameters for the triton and the He^4-ion channels were tried, and triton parameters deduced from He^3-ion parameters[8,22] were also tried. In all cases, sets were chosen in which V was greater than 100 MeV. The different sets yielded angular distributions whose shapes were very similar but whose magnitudes differed by as much as 15 to 20% from the original set. For any given set, however, this change in magnitude was approximately the same for all angular momentum transfers ($l = 0, 1, 2, 3$).

In the DW calculation employed, the form factor is obtained from a particle moving in a Saxon well. We used a well with a radius of $1.25A^{1/3}$ F and a diffuseness parameter of 0.65 F, in which the proton was bound with an energy equal to its separation energy. The effect of varying the depth and shape of this well was not examined.[23] An integration cutoff radius[24] of 5.1 F was used in the calculation of the distributions shown in Fig. 3; allowing the cutoff to occur at smaller radii up to and including the origin yielded only minor changes in the shapes of the predicted distributions, but produced changes in magnitude of up to 15%. This was also the behavior when the other optical-model sets mentioned in the preceding paragraph were used.

The DW predictions for the ground-state and the 1.37-MeV state distributions (see Fig. 3) reproduce their general features, but fail to reproduce their de-

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[14] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1961), NRC 61-2-14.

[15] G. Chilosi, S. Monaro, and R. A. Ricci, Nuovo Cimento **26**, 440 (1962).

[16] L. S. August, C. R. Gossett, and P. A. Treado, Phys. Rev. **142**, 664 (1966).

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[19] We are indebted to R. M. Drisko and R. H. Bassel for furnishing us with the T-SALLY distorted-wave program.

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[21] A. G. Blair, J. C. Hafele, and D. D. Armstrong, Bull. Am. Phys. Soc. **11**, 98 (1966).

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[24] R. M. Drisko and G. R. Satchler, Phys. Letters **9**, 342 (1964).

tailed structure. Of the two remaining cases of Fig. 3, the $l=2$ prediction matches much more closely the experimental distribution for the 3.54-MeV state, while the $l=0$ prediction represents the data quite well in the vicinity of the first maximum, but then falls out of phase. The predicted DW curves have been arbitrarily normalized to the data in the region of the experimental maximum; this procedure was followed for all distributions. The results shown in Fig. 3 are fairly typical of the results for all the Ni nuclides.

The relation between the cross section σ predicted by the DW calculation and the experimental cross section $d\sigma/d\Omega$ is given by

$$d\sigma/d\Omega=\tfrac{1}{2}NS\sigma\,,$$

where N is a normalization factor and S is the spectroscopic (nuclear overlap) factor. The factor $\frac{1}{2}$ comes from the term $(2i_4+1)/(2i_3+1)$, where i_4 and i_3 are the spins of the He^4 ion and the triton, respectively. In the present work we have taken the value $N=38$ for spinless-proton pickup. This is the average value obtained empirically from comparison of the (He^4,t) reaction to the (He^3,d) reaction on several isotopes in this mass region.[1]

The effect of a $\boldsymbol{\sigma}\cdot\mathbf{l}$ potential for the bound-state well has been simulated by assuming a j dependence for N. This dependence is taken to be identical to that used in the DW analysis of (He^3,d) and (He^4,t) reaction data,[1,8,25] i.e., a 10% increase (decrease) in N for a $p_{3/2}(p_{1/2})$ transition, and proportional to $(2l+1)$.

Column 4 of Table II shows the values of S obtained for the $\mathrm{Ni}^{58}(t,\mathrm{He}^4)\mathrm{Co}^{57}$ reaction for the spin and parity assignments of column 3. In making those assignments, we have assumed that we pick up only $2p_{3/2}$, $1f_{7/2}$, $1d_{3/2}$, and $2s_{1/2}$ protons in the excitation energy interval observed. We are also aided by the observation that the Q dependence of the distributions appears to be small and regularly behaved. The evidence for this is found in the comparison of distributions from states in all four nuclei whose spin and parity assignments can be considered reasonably firm, and from the systematic behavior of distributions within a given nucleus. Coupled with the predictions of the DW calculation, these considerations lead us to the spin and parity assignments of Table II (and the following three tables). The assignments to the weakly excited states between 2 and 4 MeV of excitation are less certain than are those to the strongly excited states, and in those cases where the interpretation is especially difficult the assumed values of J^π are enclosed in parentheses.

Comparison between Table II and Fig. 2 shows that the distributions in the figure have been arranged according to l transfers, with $l=3$ and $l=2$ on the left, and $l=1$ and $l=0$ on the right. The distributions from the 1.22- and the 1.68-MeV states are exceptions to this arrangement; it is not possible to assign an l transfer to these two distributions. (The 21° spectrum of Fig. 1 provides scant evidence of the existence of the 1.68-MeV state, but at nearly all other angles its reality is quite apparent.) These two states have not been previously reported. Although weakly excited, they are probably true Co^{57} states rather than peaks due to a target contaminant. This statement is supported by the following argument. The behavior of these peaks with respect to kinematic shifts is indistinguishable from that of nearby known Co^{57} peaks over the angular interval studied. If the peaks were due to the presence of a contaminant element in this mass region, one would expect that they would have recognizable angular distributions, since in order to make their appearance they would presumably correspond to strong transitions from the occupied proton orbitals. This is not the case; the distributions do not resemble those of any strong Co^{57} transition.

There are several small peaks below 3 MeV in the Co^{57} spectrum (Fig. 1) and the spectra of the other Co nuclides which are unlabeled and do not appear in the tables. The behavior of these peaks from one angle to the next is rather erratic, and it is not certain that they are true Co peaks.

The present results are in qualitative agreement with the $\mathrm{Ni}^{58}(n,d)\mathrm{Co}^{57}$ reaction results of Wang and Winhold.[3] These authors report a strong $l=3$ transition to the ground state and to a state at 1.88 MeV, and a relatively strong transition to the $\frac{3}{2}^-$ 1.37-MeV state. If the spectroscopic factors of Wang and Winhold are renormalized to allow a total of 8 protons above the $2s$-$1d$ shell, their results for the ground state and the 1.88-MeV state are in fair quantitative agreement with ours. However, their spectroscopic factor for the 1.37-MeV state is still several times higher than ours. The comparison is made difficult, however, by the 250-keV resolution of the (n,d) reaction study. In the present

TABLE II. Results from the $\mathrm{Ni}^{58}(t,\mathrm{He}^4)\mathrm{Co}^{57}$ reaction.

E_{ex} (MeV)	ΔE_{ex} (MeV)[a]	Assumed J^π	S
0	...	$\frac{7}{2}^-$	5.53
1.218	0.015	...	...
1.369	0.015	$\frac{3}{2}^-$	0.06
1.683	0.015	...	...
1.747	0.015	$\frac{3}{2}^-$	0.19
1.890	0.015	$\frac{7}{2}^-$	1.37
2.130	0.020	$(\frac{3}{2}^+)$	0.10
2.302	0.020	$\frac{7}{2}^-$	0.20
2.489	0.020	...	...
2.591	0.020	$\frac{7}{2}^-$	0.07
2.721	0.025	$(\frac{7}{2}^-)$	0.04
2.970	0.025	$\frac{1}{2}^+$	1.31
3.171	0.025	...	...
3.259	0.025	$(\frac{7}{2}^-)$	0.14
3.354	0.030	$\frac{7}{2}^-$	0.11
3.539	0.030	$\frac{3}{2}^+$	2.33
3.682	0.030	$\frac{7}{2}^-$	0.13
3.906	0.030	$(\frac{3}{2}^+)$	0.20
4.038	0.035	...	...
5.91	0.05	$\frac{3}{2}^+$	0.23
6.01	0.05	$\frac{3}{2}^+$	0.29

[a] The excitation energy of a state is $E_{\mathrm{ex}}\pm\Delta E_{\mathrm{ex}}$.

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[25] D. D. Armstrong and A. G. Blair, Phys. Rev. 140, B1226 (1965).

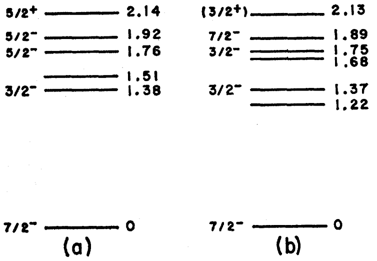

FIG. 4. Energy-level diagram of the lower excited states of Co^{57}. (a) States and assignments from August *et al.* (Ref. 16). (b) States and assignments from the present study.

experiment the average cross section of the 1.22-MeV state is approximately the same as that of the 1.37-MeV state; under the conditions of the (n,d) reaction study these two states would not be resolved.

Table II indicates that only two $l=1$ transitions, those at 1.37 and 1.75 MeV, were observed in the present work. In a recent study of the $Fe^{56}(He^3,d)Co^{57}$ reaction,[26] $l=1$ transitions were also observed at these energies. The only other $l=1$ transition observed below 2 MeV of excitation in the (He^3,d) reaction was to a state at 1.50 MeV; the lack of such a transition in the (t,He^4) reaction favors an assignment of $J^\pi=\frac{1}{2}^-$ to the state.

If the Ni^{58} ground-state wave function could be described as a closed $f_{7/2}$ proton shell plus a certain neutron configuration, and the Co^{57} ground-state wave function were formed from this by the removal of one $f_{7/2}$ proton, the only $f_{7/2}$ transition in the (t,He^4) reaction would be to the ground state, and the spectroscopic factor would be $S=8$.[27] The wave functions are not this simple, of course; nonetheless, the appearance of the rather large number of $f_{7/2}$ transitions in Table II is somewhat unexpected. Of the observed transitions, there is a possible correspondence to an $l=3$ transition observed in the (He^3,d) reaction[26] at 3.25 MeV.

A study of the $Fe^{56}(p,\gamma\gamma)Co^{57}$ reaction has been reported recently.[16] Spins and parities were assigned to some of the lower states of Co^{57}; Fig. 4(a) shows these states and their assignments. In Fig. 4(b) the results from the present experiment are shown. The only excited state assignment for which there is apparent agreement in the two studies is that at 1.37 MeV. For the 1.75-MeV state, the $l=1$ transition observed in the (He^3,d) reaction study[26] is consistent with the results of the present study, but disagrees with the $\frac{5}{2}^-$ assignment from the $(p,\gamma\gamma)$ results.[16] For the 1.89-MeV state [Fig. 4(b),] there are two arguments favoring an assignment of $J^\pi=\frac{7}{2}^-$ rather than $\frac{5}{2}^-$. First, only $J^\pi=\frac{7}{2}^-$ is permitted by the "nearly closed-shell" assumption made earlier in this section. The validity of the assumption is supported by the small total amount of $l=1(p_{3/2})$ strength found in the present study. The second argument is based on the results of recent investigations of the (He^4,t) reaction[1] and the $Zn^{64}(t,He^4)Cu^{63}$ reaction.[28] In that work it was observed that there were significant forward-angle differences between $f_{5/2}$ and $f_{7/2}$ distributions. It was a general feature that the pattern of $f_{5/2}$ distributions tended to be shifted inward several degrees relative to $f_{7/2}$ distributions. In the present case, there is no appreciable shift between the distribution from the 1.89-MeV state and known $f_{7/2}$ distributions involving similar reaction Q's (to the ground states of Co^{57}, Co^{59}, and Co^{61}). This observation supports the assignment of $\frac{7}{2}^-$ to the state.

It is possible that there are two states in the vicinity of 1.90 MeV. A recent study[29] of γ-ray transitions following the decay of Ni^{57} determined the energy of a state in this region of excitation energy as 1.9202 ± 0.0001 MeV. This result is consistent with the value of 1.921 ± 0.020 MeV obtained by August *et al.*,[16] but is somewhat outside the allowed value of 1.890 ± 0.015 MeV from the present study. These considerations suggest the presence of a doublet whose members appear at 1.89 MeV and 1.920 MeV, which have spins and parities of $\frac{7}{2}^-$ and $\frac{5}{2}^-$, respectively.

The $d_{3/2}$ distribution from the 3.54-MeV state is very similar to $f_{5/2}$ distributions observed in the $Zn^{64}(t,He^4)Cu^{63}$ reaction[28] and frequently in the (He^4,t) reaction.[1] It is unlikely that the 3.54-MeV distribution represents an $f_{5/2}$ transition, since for that case the DW calculation would yield a spectroscopic factor of $S\approx2.8$. But it is possible that some of the weak transitions

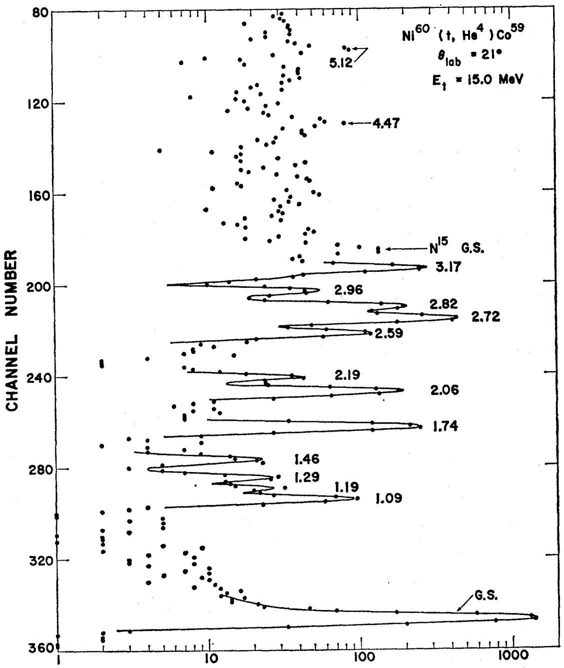

FIG. 5. Pulse-height spectrum of He^4 ions from the $Ni^{60}(t,He^4)Co^{59}$ reaction.

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[28] D. D. Armstrong and A. G. Blair (unpublished).

[29] C. J. Piluso, D. O. Wells, and D. K. McDaniels, Nucl. Phys. **77**, 193 (1966).

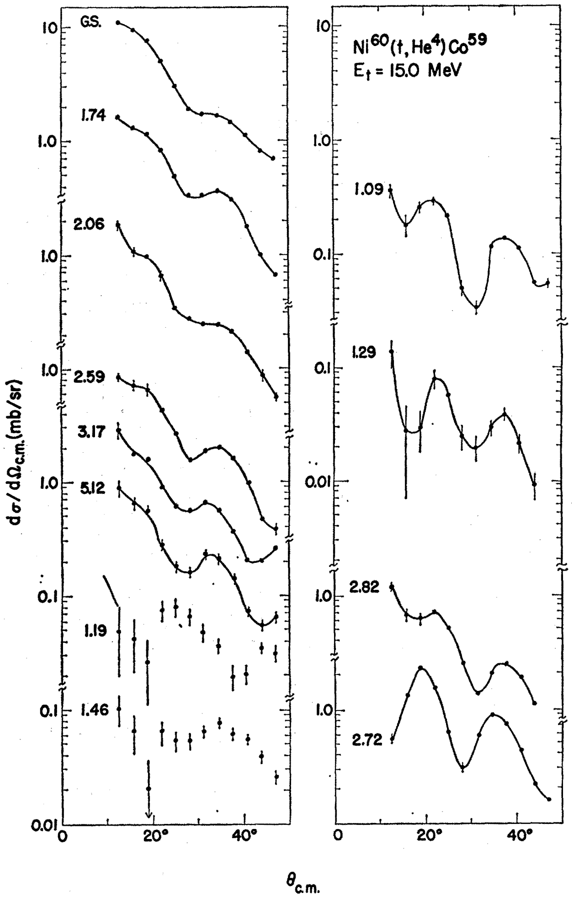

FIG. 6. Angular distributions of some of the He^4-ion groups from the Ni^{60}(t,He^4)Co^{59} reaction.

which have been represented as $d_{3/2}$ in the present study are actually $f_{5/2}$ transitions.

Although it was also observed in the (He^4,t) and (t,He^4) reaction studies mentioned above that there were often forward-angle differences between $p_{3/2}$ and $p_{1/2}$ distributions, the study[28] of the Zn^{64}(t,He^4)Cu^{63} reaction and the Zr^{90}(t,He^4)Y^{89} reaction at a triton beam energy of 15 MeV indicated that these differences are not very pronounced at this energy. It is, therefore, not possible in the present study to distinguish $p_{1/2}$ transitions from $p_{3/2}$ transitions on this basis.

The j dependence of angular distributions from the (t,He^4) reaction and its relation to DW predictions are discussed further in Sec. IV.

B. Ni^{60}(t,He^4)Co^{59}

The ground-state Q for the Ni^{60}(t,He^4)Co^{59} reaction is 10.287 MeV.[13] A typical energy spectrum for this reaction is shown in Fig. 5, and angular distributions of He^4 ions from many of the observed states are shown in Fig. 6. The distributions are arranged according to l transfers as in Fig. 2, except for the inclusion of the 1.19-MeV and 1.46-MeV states. Between the 3.17-MeV group and the 5.12-MeV group the spectral analysis yields angular distributions whose l transfers cannot be identified.

Several groups of authors have performed high-resolution inelastic scattering experiments on Co^{59}.[30–32] In Table III we show the levels observed by Bjerregaard *et al.*,[31] up to about 2 MeV of excitation. Over this range the correspondence to the levels from the (t,He^4) reaction is quite certain, and the agreement is good. The spectroscopic factors from the present study are also shown in Table III. Previous work[33] has shown that the 1.09-MeV and 1.29-MeV states have $J^\pi = \frac{3}{2}^-$ and that the most probable assignment for the fourth excited state at 1.43 MeV is $J^\pi = \frac{1}{2}^-$. The present results, in which $l=1$ transitions to the 1.09- and 1.29-MeV states are observed, but no transition to the 1.43-MeV state is observed, are consistent with these assignments. In the Fe^{58}(He^3,d)Co^{59} reaction study,[33] a broad group having an $l=3$ distribution was observed at approximately 2.08 MeV. By comparison to the levels in column 1, it seems likely that this group consists mainly of the 2.057- and 2.084-MeV states. An assignment of $J^\pi = \frac{5}{2}^-$ to the 2.084-MeV state is consistent with its strong appearance in the (He^3,d) reaction study and its failure to appear in the present (t,He^4) reaction study.

Although the presence of large error bars prevents one from drawing definite conclusions, it is interesting to note the similarity of the 1.19-MeV distribution to the Co^{57} 1.22-MeV distribution, and also of the 1.46-MeV distribution to the Co^{57} 1.68-MeV distribution.

TABLE III. Results for Co^{59}.

E_{ex} (MeV)[a] (p,p')	E_{ex} (MeV)[b] (t,He^4)	ΔE_{ex} (MeV)[b]	Assumed J^π	S (t,He^4)	S (d,He^3)
0	0	...	$\frac{7}{2}^-$	6.61	5.50
1.096	1.093	0.015	$\frac{3}{2}^-$	0.29	0.42
1.187	1.188	0.015	...	...	...
1.288	1.290	0.015	$\frac{3}{2}^-$	0.07	0.09
1.429					
1.456	1.460	0.015	...	...	...
1.478					
1.741	1.738	0.015	$\frac{7}{2}^-$	1.01	0.93
2.057	2.057	0.020	$\frac{7}{2}^-$	0.80	0.70
2.084					
2.148					
	2.191	0.020	($\frac{7}{2}^-$)	0.20	...
	2.585	0.020	$\frac{7}{2}^-$	0.61	...
	2.715	0.020	$\frac{1}{2}^+$	1.66	...
	2.818	0.025	($\frac{3}{2}^-$)	0.48	...
	2.961	0.025	...	...	...
	3.166	0.025	$\frac{3}{2}^+$	2.39	...
	5.12	0.04	$\frac{3}{2}^+$	0.62	...

[a] From Ref. 31. The errors are 5 to 7 keV.
[b] From present experiment.

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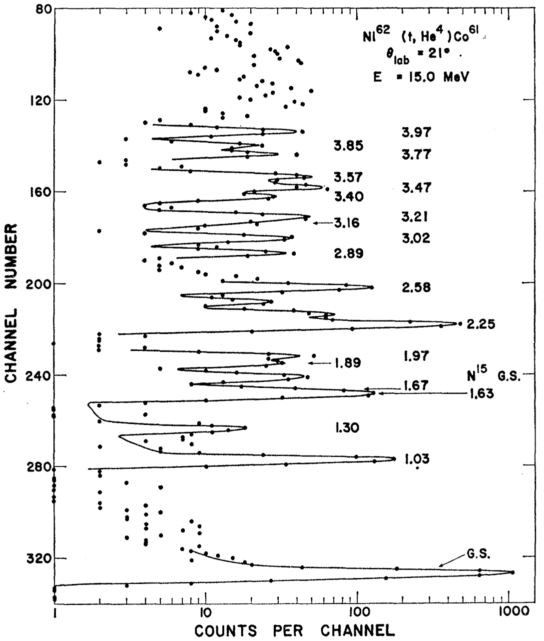

FIG. 7. Pulse-height spectrum of He^4 ions from the $Ni^{62}(t,He^4)Co^{61}$ reaction.

(See Figs. 2 and 6.) In both cases the Co^{59} cross sections are higher by about a factor of two. These two Co^{59} states have previously been observed only in (p,p') reaction studies[30–32] and in Coulomb-excitation studies.[34]

In an effort to gain additional understanding of the (t,He^4) reaction we also made a brief study of the $Ni^{60}(d,He^3)Co^{59}$ reaction. A 22-MeV deuteron beam was obtained from the three-stage Van de Graaff accelerator. Detection of particles was accomplished by means of a $\Delta E - E$ telescope and mass-identification system similar to that described previously.[8,25] Angular distributions of He^3-ion groups were obtained over the range of $10° \leq \theta \leq 42°$ and were compared to the results of a DW calculation. The results are shown in the final column of Table III. It was our hope that this study would establish angular momentum transfers and spectroscopic factors to which the (t,He^4) reaction results could be compared. The study was successful for these purposes for the ground-state transition and the transitions to excited states up to approximately 2 MeV. At higher excitation energies, however, the results were less significant, for the cross section dropped rapidly with increasing excitation energy, and the angular distributions became rather featureless. In addition, the larger cross sections associated with light-element contaminants in the target resulted in the partial obscuring of some of the Co^{59} peaks at the higher energies. For these reasons, Table III does not include (d,He^3) reaction results for the states above 2.06 MeV. No obvious inconsistencies between the two reactions appeared for any of the states observed, however.

C. $Ni^{62}(t,He^4)Co^{61}$

The ground-state Q for the $Ni^{62}(t,He^4)Co^{61}$ reaction is given as 8.707±0.040 MeV.[13] In the present experiment one can establish the Q to somewhat better accuracy by noting the position of the ground-state peak from the $O^{16}(t,He^4)N^{15}$ reaction and using the previously established energy scale; the result is $Q = 8.689 \pm 0.020$ MeV. A typical energy spectrum for this reaction is shown in Fig. 7. The peak centered at about 1.64 MeV of excitation is somewhat wider than neighboring peaks; the analysis of the data indicates the presence of two states at this position. It was not possible to obtain meaningful distributions for the states separately, although it was ascertained that the cross section of the 1.63-MeV member was the larger at nearly all angles. The composite distribution, labeled 1.64 MeV in Fig. 8, resembles the ground-state distribution. The larger error bars at the three small-angle points result from uncertainties in the subtraction of the N^{15} ground-state peak.

There is a suggestion of a state or states at approximately 1.3 MeV, but the peaks are not clearly defined at most angles.

The angular distributions in Fig. 8 are from the more strongly excited states in Co^{61}, and are arranged according to l transfers as in Fig. 2. Table IV shows the observed levels up to 4 MeV and the spectroscopic factors obtained. There is very little spectroscopic information from other studies; the present assignment of $J^\pi = \frac{7}{2}^-$ for the ground state is consistent with shell-model predictions and with previous results.[35]

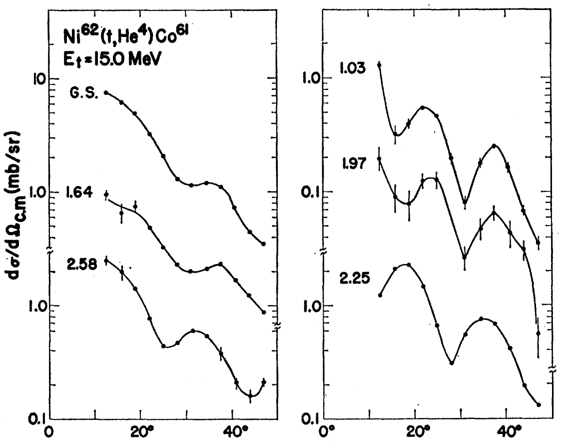

FIG. 8. Angular distributions of some of the He^4-ion groups from the $Ni^{62}(t,He^4)Co^{63}$ reaction.

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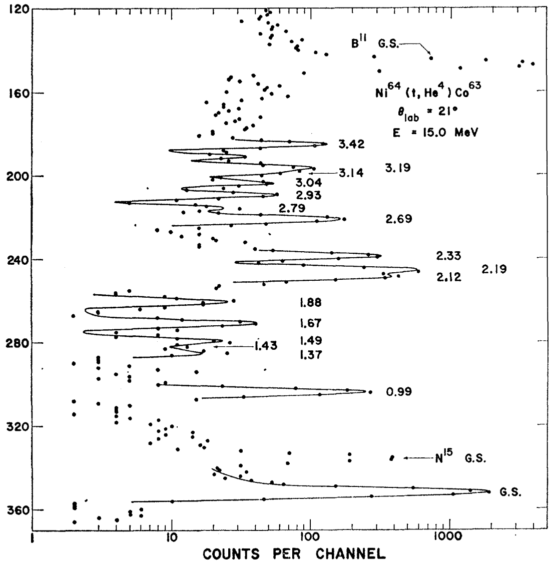

FIG. 9. Pulse-height spectrum of He^4 ions from the Ni^{64}(t,He^4)Co^{63} reaction.

D. Ni^{64}(t,He^4)Co^{63}

The ground-state Q for the Ni^{64}(t,He^4)Co^{63} reaction is given as 7.33±0.20 MeV.[13] By using the technique outlined in the previous paragraph, we have established its value as 7.266±0.020 MeV. A typical energy spectrum for the reaction is shown in Fig. 9, and the angular distributions from the more strongly excited states are shown in Fig. 10. The distributions are arranged according to l transfers as in Fig. 2. Table V lists the observed levels up to 3.5 MeV and the associated spectroscopic factors. The table indicates that for Co^{63}, as for the other Co isotopes, there are angular distributions from low-lying He^4-ion groups whose angular-momentum transfers cannot be determined. The cross sections of these groups are relatively small, lying between approximately 0.01 and 0.1 mb/sr. Above 3.5 MeV of excitation, the analysis provided no useful spectroscopic information.

From shell-model considerations, the ground-state spin and parity of Co^{63} should be $\frac{7}{2}^-$. No spectroscopic information on Co^{63} is available from previous studies.

TABLE IV. Results from the Ni^{62}(t,He^4)Co^{61} reaction.

E_{ex} (MeV)	ΔE_{ex} (MeV)	Assumed J^π	S
0	...	$\frac{7}{2}^-$	4.91
1.029	0.015	$\frac{3}{2}^-$	0.41
1.627	0.015	$\frac{7}{2}^-$	0.83
1.674	0.015		
1.893	0.015	...	...
1.966	0.020	$\frac{3}{2}^-$	0.09
2.247	0.020	$\frac{1}{2}^+$	1.41
2.575	0.020	$\frac{3}{2}^+$	1.24
2.893	0.025	$\frac{7}{2}^-$	0.15
3.022	0.025	$\frac{7}{2}^-$	0.15
3.159	0.025	...	...
3.215	0.025	($\frac{3}{2}^+$)	0.37
3.395	0.030	...	...
3.470	0.030	($\frac{7}{2}^-$)	0.33
3.573	0.030	($\frac{3}{2}^+$)	0.04
3.766	0.035	($\frac{7}{2}^-$)	0.18
3.854	0.035	$\frac{3}{2}^+$	0.31
3.975	0.035	($\frac{7}{2}^-$)	0.17

TABLE V. Results from the Ni^{64}(t,He^4)Co^{63} reaction.

E_{ex} (MeV)	ΔE_{ex} (MeV)	Assumed J^π	S
0	...	$\frac{7}{2}^-$	6.93
0.987	0.015	$\frac{3}{2}^-$	0.41
1.373	0.015	...	...
1.425	0.015	...	...
1.492	0.015	($\frac{3}{2}^-$)	0.03
1.666	0.015	...	...
1.879	0.015	($\frac{3}{2}^-$)	0.06
2.121	0.020	$\frac{7}{2}^-$	1.36
2.186	0.020	$\frac{1}{2}^+$	1.19
2.329	0.020	$\frac{7}{2}^-$	1.12
2.690	0.025	$\frac{3}{2}^+$	1.42
2.932	0.025	$\frac{7}{2}^-$	0.25
3.040	0.025	$\frac{7}{2}^-$	0.20
3.137	0.025	...	...
3.189	0.025	$\frac{7}{2}^-$	0.42
3.421	0.030	...	...

IV. DISCUSSION

In Table VI we have assembled the results from Table II to V as sums of spectroscopic factors for each of the shell-model states. The table also includes the observed energy centroids of each of these states.

According to our assumption concerning the ground-state wave functions of the Ni nuclei, the sums of spectroscopic factors for $1f_{7/2}$ and $2p_{3/2}$ transitions should total 8.[27] The results are fairly satisfactory; the largest discrepancy from this prediction is for Co^{63}, where the experimental total is 35% higher. It is to be noted that there are two entries for the $(2p_{3/2})^{-1}$ shell-model state

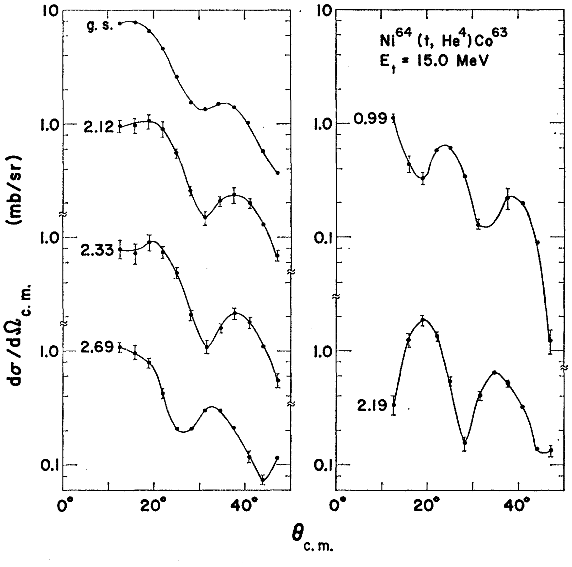

FIG. 10. Angular distributions of some of the He^4-ion groups from the Ni^{64}(t,He^4)Co^{63} reaction.

TABLE VI. Sums of spectroscopic factors and energy centroids from (t,He^4) reaction.

Shell-model state	Co^{57} $\sum S$	Co^{57} centroid (MeV)	Co^{59} $\sum S$	Co^{59} centroid (MeV)	Co^{61} $\sum S$	Co^{61} centroid (MeV)	Co^{63} $\sum S$	Co^{63} centroid (MeV)
$(1f_{7/2})^{-1}$	7.59	0.61	9.23	0.59	6.72	0.71	10.28	0.80
$(2p_{3/2})^{-1}$	0.25	1.66	0.36 (0.84)	1.15[a] (2.10)	0.50	1.21	0.51	1.13
$(2s_{1/2})^{-1}$	1.31	2.97	1.66	2.71	1.41	2.25	1.19	2.19
$(1d_{3/2})^{-1}$	3.15	3.92	3.01	3.57	1.96	...	1.42	...

[a] The top entry corresponds to the inclusion of only the 1.09- and 1.29-MeV states, while the entry enclosed in parentheses also includes the 2.82-MeV state.

in Co^{59}. The top entry corresponds to the inclusion of only the 1.09-MeV and 1.29-MeV states, while the entry enclosed in parentheses also includes the state at 2.82 MeV, the assignment of which is somewhat uncertain.

The sum of spectroscopic factors for the $2p_{3/2}$ transitions for Co^{61} and for Co^{63} is consistent with the results from the study of the (He^3,d) reaction on Ni^{62} and Ni^{64},[8] which indicated that the $2p_{3/2}$ orbital in these two Ni nuclides is approximately 12% filled.

The sum of spectroscopic factors for the $2s_{1/2}$ transitions should be 2.[27] In each of the nuclei only one $l=0$ transition was observed; Table VI assumes that all the $2s_{1/2}$ strength is carried in this transition. In each case the experimental value for the transition is somewhat low. It is possible that there are significant fragments of the $2s_{1/2}$ hole state which remain undetected, but it seems more likely that the failure is in the predictions of the DW calculation (as we have employed it).

The sum of spectroscopic factors for the $1d_{3/2}$ transitions should be 4.[27] Although in each nucleus there is only one strong transition identified as $d_{3/2}$, there are weaker He^4-ion groups which are also identified as $d_{3/2}$ transitions. As pointed out earlier in this report, it is possible that some of these are $f_{5/2}$ transitions. In addition, there are groups at 6 MeV in Co^{57} and at 5 MeV in Co^{59} whose angular distributions lead to $l=2$ assignments. It may be that these are actually fragments of the $d_{5/2}$ rather than the $d_{3/2}$ hole state. For Co^{61} and Co^{63} no transitions corresponding to the 6-MeV and 5-MeV transitions in Co^{57} and Co^{59} could be identified. The sums of the observed $d_{3/2}$ spectroscopic strength are rather small for Co^{61} and Co^{63}, and no centroid value is shown for them.

From these results it is clear that there are many similarities in the spectroscopy of the four Co nuclides. A summary of the most prominent of these follows:

(1) There is a strong $f_{7/2}$ transition to the ground state.

(2) There are several additional $f_{7/2}$ transitions, some of them fairly strong, to states above 1.5 MeV.

(3) One and only one strong $s_{1/2}$ transition appears in each nuclide.

(4) Approximately 30 to 60 keV above the $s_{1/2}$ transition a strong $d_{3/2}$ transition appears. There is some evidence that not all of the strength of $(d_{3/2})^{-1}$ shell-model state appears in this transition, however.

(5) There is at least one $p_{3/2}$ transition in the vicinity of 1 MeV.

Remark (2) indicates that there is a dissimilarity between the Ni and the Co ground-state wave functions, and suggests that several configurations contribute to the ground-state wave function of Co. Remarks (3) and (4) place the $s_{1/2}$ transition at a lower excitation energy than the strong $d_{3/2}$ transition. In the study[17] of the Sc nuclides by means of the (d,He^3) reaction on Ti nuclides, the ordering was found to be inverted from this. Furthermore, the excitation energy of these states decreases with increasing mass for the Co nuclides, but increases with increasing mass for the Sc nuclides.[17]

The recent study[1] of the (He^4,t) reaction provided evidence for a strong Q dependence of the experimental angular distributions. The results suggested that this behavior might be traced to a strong dependence upon the energy of the triton channel. The results from the present study, in which the triton energy is fixed, are consistent with this proposal, for the experimental distributions change slowly and in a regular fashion within each nuclide and from one nuclide to another.

The j-dependent behavior of the angular distributions observed in the (He^4,t) reaction study[1] cannot be reproduced by a spinless-particle DW calculation. This behavior, as well as the poor agreement between the experimentally observed $\frac{3}{2}^-$ and $\frac{7}{2}^-$ distributions and the calculated distributions in the present investigation, suggests the inclusion of a spin-orbit term for the triton channel in the DW calculation. Unfortunately, there is no experimental information concerning the magnitude and radial dependence of such a term. A preliminary calculation has been made by Bassel,[22] who assumed a potential of the form

$$V_s(h/m_\pi c)^2 \boldsymbol{\sigma}\cdot\mathbf{L} r^{-1}(d/dr)(e^x+1)^{-1},$$

where x refers to the real-well geometry as before. The optical-model parameters used in the calculation were somewhat different than those in Table I. The triton parameters were those deduced from He^3-ion parameters,[8,22] while the He^4-ion parameters came from earlier analyses.[22] The DW calculation was performed for $l=1$

and $l=3$ transitions in the $Ni^{62}(t,He^4)Co^{61}$ reaction, for well depths $V_s=4$ and 8 MeV. The calculation also included a spin dependence in the bound-state well. The predicted distributions were nearly identical to those obtained for spinless particles. This behavior is somewhat surprising in view of the very definite $\mathbf{S}\cdot\mathbf{L}$ dependence predicted for the (He^4,p) reaction[36] and for the (p,He^4) reaction.[37] It is possible that the geometry of the spin-orbit potential well differs from that of the real potential well for highly absorbed particles such as tritons.

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Stripping Analysis of the $Sc^{45}(d,p)Sc^{46}$ Reaction*

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The $Sc^{45}(d,p)Sc^{46}$ reaction has been studied with a multiple-gap magnetic spectrograph and the MIT-ONR electrostatic accelerator. Eighty-four energy levels were observed, and angular distributions of the corresponding proton groups were analyzed up to an excitation energy of 4.0 MeV. Eighty-five additional energy levels in Sc^{46} were observed between 4.0 and 6.0 MeV where the level density is seen to increase rapidly with excitation energy. Some unresolved particle groups are estimated to have separations of a few keV. The ground-state Q value was measured to be 6.541 ± 0.008 MeV. The angular distributions were measured in 7.5-deg intervals between 7.5 and 172.5 deg. The assignments of the captured-neutron angular-momentum l_n were based on the position of the first maximum as predicted by a distorted-wave Born-approximation theoretical calculation. The transition strengths for the groups, for which l_n assignments were made, were determined from the measured differential cross sections and the predictions of the distorted-wave, deuteron-stripping analysis.

I. INTRODUCTION

INVESTIGATIONS of energy levels in Sc^{46} have in the past been restricted mainly to two modes of excitation: the (n,γ) and (d,p) reactions on the mono-isotopic element Sc^{45}. More recently, with the use of both higher bombarding energies and He^3-induced reactions,[1] it has been possible to study Sc^{46}, as well as other unstable scandium isotopes, by means of reactions involving the stable neighboring nuclei of calcium and titanium.

The earliest measurements of high-energy neutron-capture gamma rays were made by Bartholomew and Kinsey.[2] Eight gamma rays with energies between 6.35 and 8.85 MeV were measured, and if they are assumed to correspond to direct transitions from the capture state, then several states in Sc^{46} may be predicted. Groshev *et al.*[3] have extended these measurements to lower energy gamma rays (1.1 MeV) and report an additional 16 gamma rays associated with transitions in Sc^{46}.

The isomeric level at 142 keV in Sc^{46} has been known from the early work of Goldhaber and Muehlhause[4] from range measurements of internal-conversion electrons following the bombardment of Sc^{45} with slow neutrons.

Improved high resolution and coincidence techniques in gamma-ray spectroscopy have been used recently to study the decay characteristics of cascade gamma rays following direct transitions from the neutron capture state in Sc^{45}. Neill *et al.*,[5] using slow neutrons from the

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